

# Simulation and Analysis of Control Strategies for DSTATCOM

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**Abstract**—Reactive power and supply unbalance compensation in power distribution network is a key factor in improving quality at user end. Further, the control techniques applied to the DSTATCOM play major role in its performance. A Distribution Static COMPensator (DSTATCOM) has been proposed for compensation of reactive power and unbalance caused by various loads in distribution system. An evaluation of three different methods has been made to derive reference currents for a DSTATCOM. These methods are an instantaneous reactive power theory (IRP), SRF theory and Instantaneous current component theory. These schemes have been simulated under MATLAB environment using Sim Power system toolboxes. Simulation and experimental results demonstrate the performance of these schemes for the control of DSTATCOM.

**Index Terms**—Distribution Static COMPensator (DSTATCOM), Instantaneous reactive power theory (IRP) and Modified SRF theory ( $i_d-i_q$ ), Synchronous Reference Frame (SRF), Reactive power compensation, unity power factor

## I. INTRODUCTION

Variable reactive power compensation of nonlinear and/or poor power factor loads is an important issue in the modern distribution system. Moreover situation worsens in the presence of unbalanced loads. Excessive reactive power demand increases feeder losses and reduces active power flow capability of the distribution system where as unbalancing affects the operation of transformers and generators [1]. A Distribution Static COMPensator (DSTATCOM) is a custom power device connected in shunt with the load. DSTATCOM could be used for reactive power compensation and balanced loading in the distribution system [2]. The performance of DSTATCOM depends on the control algorithms used for the extraction of reference current component. In this paper, DSTATCOM has been controlled using Instantaneous reactive power theory (IRP), SRF theory and Instantaneous current component theory ( $i_d-i_q$ ) for reactive power compensation. In this paper, comparison of these three algorithms has been carried out. This paper is organized as follows: section II presents basic circuit diagram of DSTATCOM system. Section III discusses Instantaneous reactive power theory (IRP)

and Instantaneous current component theory ( $i_d-i_q$ ) in detail for the calculation of reference current injected to serve the required objective. Section IV presents the results of applying control strategies to a unique platform designed in Matlab-Simulink frame demonstrate the effectiveness of these three control algorithms for reactive power compensation resulting unity power factor. Finally section V presents conclusion.

## II. SYSTEM CONFIGURATION

Fig 1 shows the basic circuit diagram of a DSTATCOM with various types of loads connected to three-phase three-wire distribution system. DSTATCOM has been realized by 3-phase voltage source inverter. The voltage source inverter topology has been used because it could be expandable to multilevel, multi-step and chain converters [3] to enhance the performance with lower switching frequency and increased power handling capacity. In addition to this, this topology can exchange a considerable amount of real power with energy storage devices in place of the DC capacitor [4]. At AC side, the interfacing inductors  $L_f$  have been used to filter out high-frequency components of compensating currents.

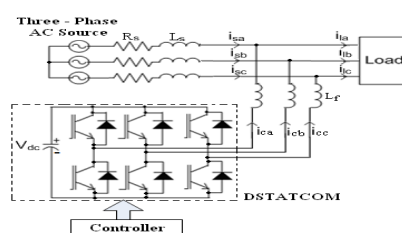


Fig.1 System Configuration

Hysteresis current controller has been used to operate switches of inverter in such a way that compensating currents would tend to follow reference currents calculated by control algorithms.

## III. CONTROL ALGORITHMS

DSTATCOM is a shunt compensator. It injects current in shunt with the load. For reactive power compensation, a DSTATCOM provides reactive power

to the load and therefore source supplies only real power to the load. Thus unity power factor of source currents could be achieved. Reference compensator currents calculated by control algorithms have been used to decide switching of DSTATCOM.

#### A. IRP Theory

In 1983 Akagi et al. [5] proposed a new theory for the control of active filters in three-phase power systems called "Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as "*p-q* Theory".

Since the *p-q* theory is based on the time domain, it is valid both for steady-state and transient operation, as well as for generic voltage and current waveforms, allowing the control of the active filters in real-time. The basic block diagram of *p-q* theory is shown in Fig.-2

$$I_{Comp} = I_{Source} - I_{Load} \quad (1)$$

Where  $I_{Comp}$  is the compensation current,  $I_{Source}$  is the source current and  $I_{Load}$  is the load current, respectively. The instantaneous power theory implements a transformation from a stationary reference system in *a-b-c* coordinates, to a system with coordinates  $\alpha-\beta-0$  by making use of an algebraic transformation, known as Clarke transformation.

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (2)$$

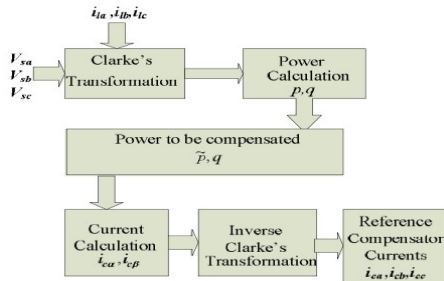


Fig. 2 Basic block diagram of *p-q* theory

$$\begin{bmatrix} P_0 \\ P \\ Q \end{bmatrix} = \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

(2) is valid for current transformation also. For three phases three wire system  $i_0=0$ , so zero sequence power  $P_0=0$ , and consequently power equation would be

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (4)$$

Using (4) the instantaneous active and reactive load powers could be obtained by following

$$\begin{bmatrix} P_t \\ Q_t \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_{t\alpha} \\ i_{t\beta} \end{bmatrix} \quad (5)$$

Which could be decomposed into oscillatory and average component. Under balanced and sinusoidal

mains voltage conditions the average power components are related to the first harmonic current of positive sequence and the oscillatory components represent all higher order current harmonics including the first harmonic current of negative sequence. Thus, the DSTATCOM should compensate the oscillatory power components so that the average power components remain in the mains.

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ 1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (7)$$

#### B. SRF Theory

SRF theory is based on the transformation of currents in synchronously rotating *d-q* frame [6] [7]. Fig. 3 shows the basic building blocks of this theory. Sensed inputs  $V_{sa}$ ,  $V_{sb}$ , and  $V_{sc}$  and  $i_{la}$ ,  $i_{lb}$ , and  $i_{lc}$  are fed to the controller. Voltage signals have been processed by a phase-locked loop (PLL) [8] to generate unit voltage templates (sine and cosine signals). Current signals have been transformed to *d-q* frame, where these signals are filtered and transformed back to *abc* frame, which are fed to a hysteresis-based PWM signal generator [9] to generate final switching signals fed to the DSTATCOM; therefore, this block works as a controller for DSTATCOM shown in Fig. 1. Similar to the *p-q* theory, current components in  $\alpha-\beta$  coordinates have been generated, and using  $\theta$  as a transformation angle, these currents have been transformed from  $\alpha-\beta$  to *d-q* frame defined as (Park's transformation)

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \quad (8)$$

SRF isolator extracts the dc component by low-pass filters (LPFs) for each  $i_d$  and  $i_q$  realized by moving average at 100 Hz. The extracted dc components  $i_{ddc}$  and  $i_{qdc}$  have been transformed back into  $\alpha-\beta$  frame using reverse Park's transformation

$$\begin{bmatrix} i_{l\alpha dc} \\ i_{l\beta dc} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_{ld dc} \\ i_{lq dc} \end{bmatrix} \quad (9)$$

From these currents, the transformation has been made to obtain three-phase reference source currents in *a-b-c* coordinates using (7). Reactive power compensation could also be provided by keeping  $i_q$  component zero for calculating the reference source currents.

#### C. Modified SRF Theory

The instantaneous active and reactive current ( $i_d-i_q$ ) method had been reported in [10] is identical to the SRF method. In this method the compensating currents have been obtained from the instantaneous active and reactive current components and of the nonlinear load. In the same way, the mains voltages  $V_{(a,b,c)}$  and the

polluted currents  $i_{l(a,b,c)}$  in  $\alpha$ - $\beta$  components must be calculated as given (10) and (11).

$$\begin{bmatrix} V_{\alpha} \\ V_{\beta} \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (11)$$

However, the  $d$ - $q$  load current components have been derived from a synchronous reference frame based on the Park transformation, where  $\theta$  represents the instantaneous voltage vector angle (12)

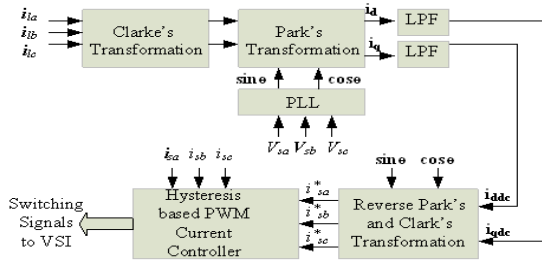


Fig. 3 Basic Synchronous Reference Frame Configuration

$$\theta = \tan^{-1} \frac{V_{\beta}}{V_{\alpha}} \quad (12)$$

Under balanced and sinusoidal mains voltage conditions angle  $\theta$  is a uniformly increasing function of time. This transformation angle has been sensitive to voltage harmonics and unbalance; therefore  $d\theta/dt$  may not be constant over a mains period. With transformation (11) the direct voltage component is  $V_d = V_{\alpha}^2 + V_{\beta}^2$ , and the quadrature voltage component is null  $V_q = 0$ , so due to geometric relations (4) becomes

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \frac{1}{\sqrt{V_{\alpha}^2 + V_{\beta}^2}} \begin{bmatrix} V_{\alpha} & V_{\beta} \\ -V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \quad (13)$$

Instantaneous active and reactive load currents and could also be decomposed into oscillatory and average terms. The first harmonic current of positive sequence has been transformed to dc quantities; this constitutes average current components. All higher order current harmonics including the first harmonic current of negative sequence have been transformed to non-dc quantities and undergo a frequency shift in the spectra, and so, constitute the oscillatory current components. These assumptions are valid under balanced and sinusoidal mains voltage conditions. The fundamental currents of the  $d$ - $q$  components have now become dc values. The harmonics would appear like ripple.

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \frac{1}{\sqrt{V_{\alpha}^2 + V_{\beta}^2}} \begin{bmatrix} V_{\alpha} & -V_{\beta} \\ V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (15)$$

One of the characteristics of this method is that the compensating currents have been calculated directly from the mains voltages, enabling the methods to be frequency independent. Avoiding the use of a PLL a large frequency operating range could be achieved limited chiefly by the cut off frequency of the current control system (VSC and current controller). Furthermore, under unbalanced and non sinusoidal mains voltage conditions, a large number of synchronization problems have been avoided especially if a PLL has been synthesized with a fast dynamic response.

$$\cos \theta = \frac{V_{\alpha}}{\sqrt{V_{\alpha}^2 + V_{\beta}^2}} \quad \sin \theta = \frac{V_{\beta}}{\sqrt{V_{\alpha}^2 + V_{\beta}^2}} \quad (16)$$

#### IV. SIMULATION RESULTS

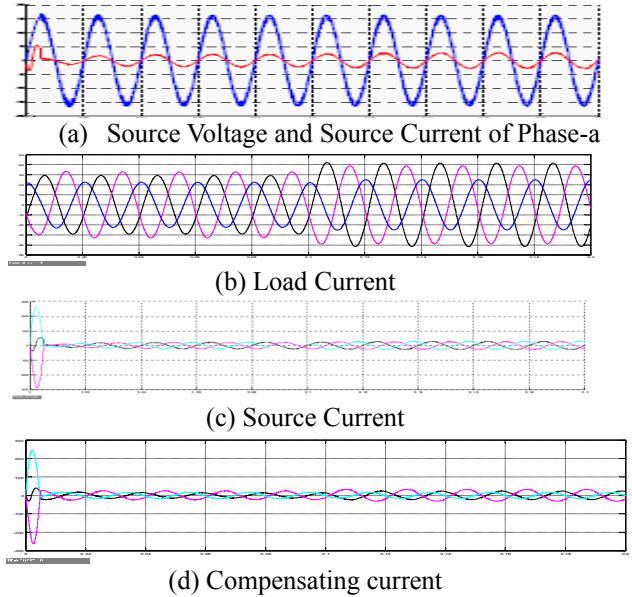


Fig. 4 Dynamic Response of DSTATCOM using IRP theory with Linear Unbalanced Load

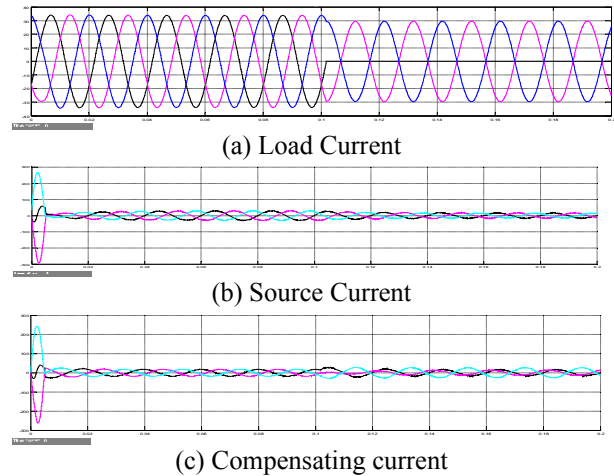


Fig. 5 Dynamic Response of DSTATCOM using IRP theory with Linear Load and one phase outage

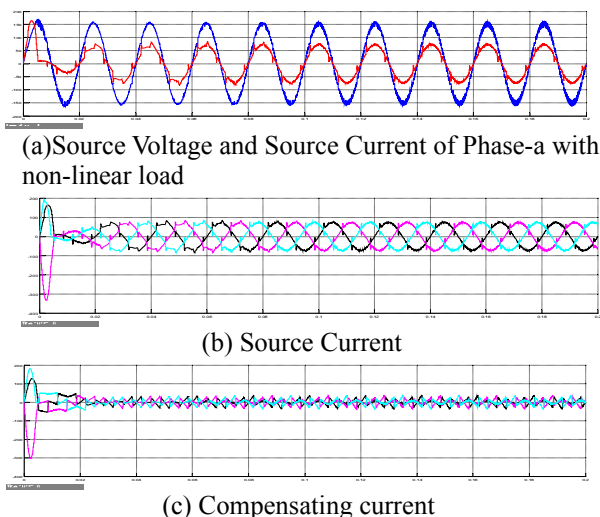


Fig. 6 Dynamic Response of DSTATCOM using IRP theory with Non-linear Load

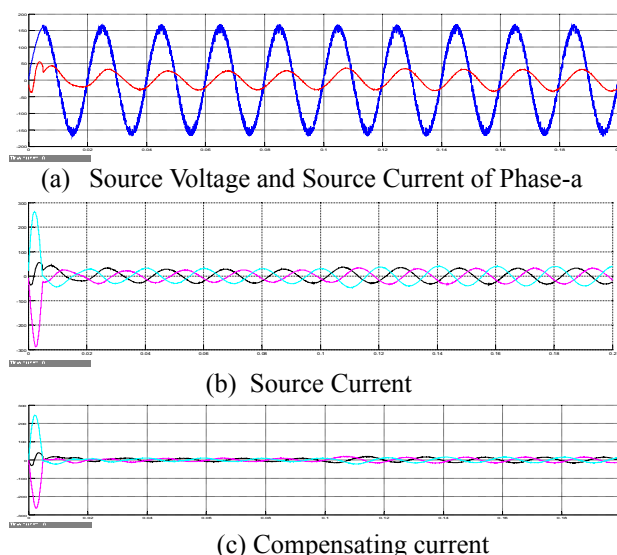


Fig. 7 Dynamic Response of DSTATCOM using SRF theory with Linear Unbalanced Load

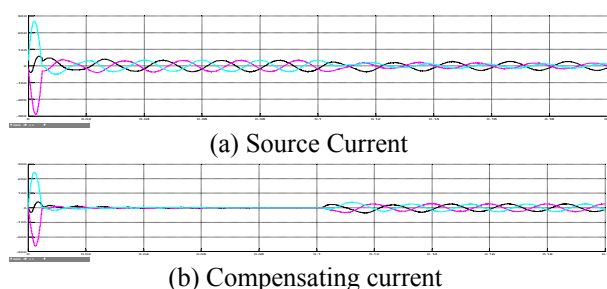


Fig. 8 Dynamic Response of DSTATCOM using SRF theory with Linear Load and one phase outage

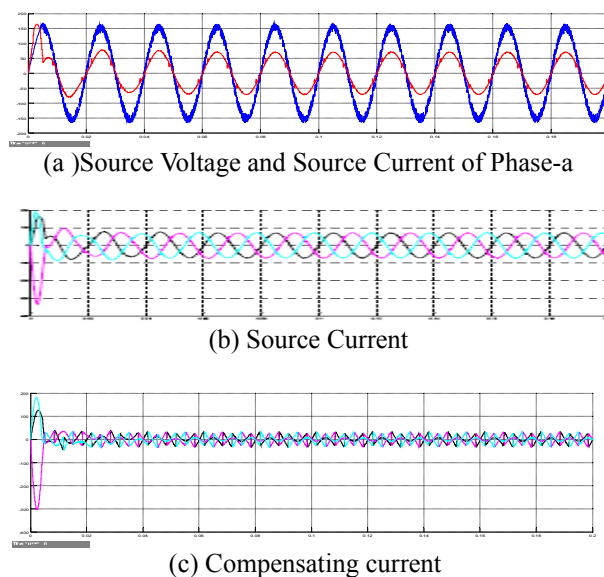


Fig. 9 Dynamic Response of DSTATCOM using SRF Theory with Non-linear Load

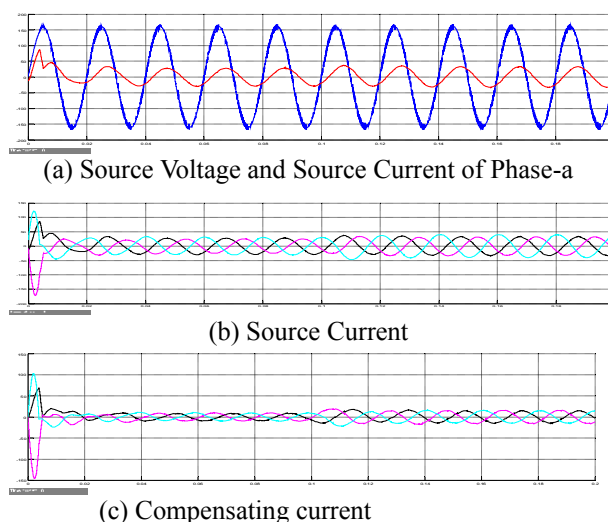


Fig. 10 Dynamic Response of DSTATCOM using Modified SRF theory with Linear Unbalanced Load

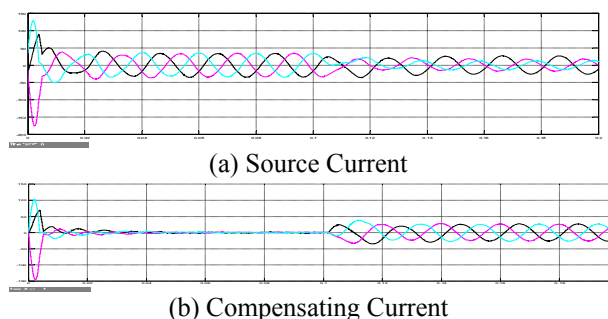


Fig. 11 Dynamic Response of DSTATCOM using Modified SRF theory with Linear Load and one

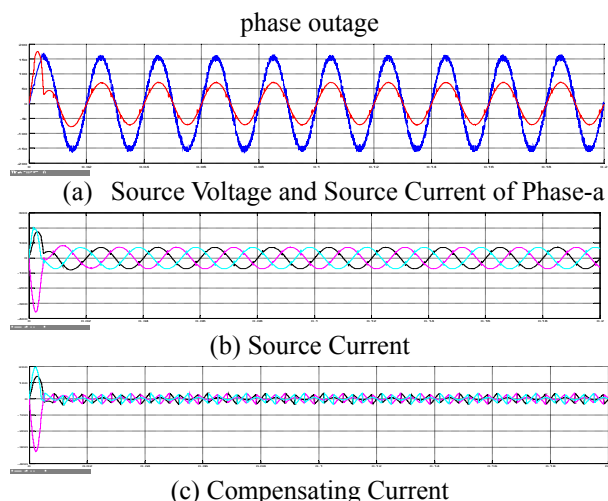


Fig. 12 Dynamic Response of DSTATCOM using Modified SRF theory with Non-linear Load

## V. CONCLUSION

The paper presents the comparative study of three different algorithms used for DSTATCOM. All Control algorithms have been described with the help of simulation results under linear and non-linear load conditions. In case of non-linear load, harmonic compensation has been better achieved by all three methods. In case of unbalanced load condition and linear load phase outage, IRP theory has shown better performance compared to SRF theory and Modified SRF theory.

## APPENDIX

V (peak value) = 200 V,  $R_s = 0.1 \Omega$ ,  $L_s = 0.05$  mH

Non-Linear Load

$R_L = 4 \Omega$ ,  $L_L = 0.01$  H,  $L_{af} = 1.5$  mH,

Linear-Unbalanced Load

$R_{La} = 4 \Omega$ ,  $L_{La} = 0.008$  H,  $R_{Lb} = 4 \Omega$ ,  $L_{Lb} = 0.01$  H,  $R_{Lc} = 5 \Omega$ ,  $L_{Lc} = 0.02$  H,  $L_{af} = 1.5$  mH,

Phase "a" Outage (Switching at 0.1 sec)

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